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BONDING SHEAR STRENGTH IN TIMBER AND GFRP GLUED WITH EPOXY ADHESIVES

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ABSTRACT

The bonding quality of epoxy glued timber and glass fibre reinforced polymers (GFRP) was evaluated by means of compression loading shear test. Three timber species (Radiata pine, Laricio pine and Oak) and two kinds of GFRP (plates and rods made with polyester resin reinforced with mat and roving glass fibre) were glued and tested using three epoxy formulations. The increase in shear strength with age after the setting of epoxy formulations and the effect of surface roughness on timber and GRP gluing (the planing of the surface of timber and the previous sanding of GRP) were studied. It can be concluded that the mechanical properties of these products make them suitable for use in the reinforcement of deteriorated timber structures, and that a rough timber surface is preferable to a planed one, while the previous sanding of GRP surfaces is not advantageous.

KEYWORDS: Wood, structural bonded joints, epoxy adhesive, glass fibre reinforced polymers.

INTRODUCTION

One of the modern techniques for strengthening and repairing timber pieces in existing and historic structures consists of using reinforcement materials such as glass fibre reinforced polymers (GFRP) and steel, connected to timber by means of gluing. The GFRP (usually glass fibre reinforced epoxy or polyester resin) are preferable to steel because of their superior behaviour in case of fire; steel has a high thermal conductivity and can easily transmit heat to the epoxy resin with the consequent lost of the mechanical properties of the connexion. Furthermore, other advantages arise from the use of GFRP such as the improvement in the ductility of pieces glued using spikes of fibreglass pultruded rods (Radford et al. 2002).

The epoxy adhesive family includes a wide variety of products with different properties, and there are suitable formulations for each application. Epoxy resins are the main adhesive used in this technique, thanks to their negligible shrinkage while curing, which makes it possible to fill the gaps between wood and the reinforcing material without the problem suffered by other adhesives of decreasing volume. In general the shear strength of other types of adhesives is significantly affected by the thickness of the glue line, so that strength decreases as the thickness of the glue line increases; this is the case of urea formaldehyde (UF) and phenol resorcinol (PR) (Tankut 2007), and even with gap-filling phenol resorcinol formaldehyde (GPRF) adhesive (Kurt 2006). Furthermore, their polymerization process is fast, so that repair works progress swiftly.

This technology has been used for reinforcing and repairing timber structures from the 1970s. One of the first research works on timber structures consisted of the use of pressure-injected epoxy to repair damaged timber buildings. The aim of this work was to establish a procedure to repair truss members in the roof of several World War II buildings at Robin Air Force Base, Georgia, USA. It consisted of experimental work, including a first part that studied epoxy to wood bond characteristics, while a second part examined the behaviour of epoxy-repaired bolted connections (Avent et al. 1976). After this experience the technology was used for the repair of full-scale timber trusses. Seven 9 m span Pratt trusses constructed with new timber and six 11 to 12 m span Fink trusses taken directly from old Air Force buildings being demolished were tested after conventional and epoxy repair (Avent et al. 1978). They also carried out in-place repair by epoxy injection in two wooden trusses, to determine whether this repair technique was economically and technically feasible (Sanders et al. 1978).

A system for the repair of rotten beam ends was developed in Holland. It consists of the substitution of deteriorated timber by epoxy mortar connected to sound timber using polyester resin glass fibre reinforced rods designated the BETA system (Klapwijk 1978). At the end of the 1970s the Association for the Preservation of Technology in Canada proposed reinforcing timber structures using composite materials (rods and plates of glass polyester resin reinforced with glass fibre) glued by epoxy resins to timber (Stumes 1979), designated the Wood Epoxy Resin (WER) system. More recently the Resiwood system appeared in the United Kingdom, manufactured by Rotafix Resins (Smedley et al. 2006, Alam et al. 2006).

In this technique three different materials work together: wood, GFRP and epoxy resin. Wood has very different physical and mechanical behaviour in comparison to the reinforcement material. Their elastic constants and behaviour under variable hydrothermal conditions are completely different. Although an increase in temperature causes the dilatation of materials, in the case of wood the effect of shrinkage due to loss of moisture content is higher than its thermal dilatation, so that it contracts. Therefore, connecting both materials by means of epoxy resin has to be able to resist the consequences of this different behaviour. The use of thick epoxy bond lines for gluing FRP to wood, in the order of 2 mm, is common practice in industry and in research programmes, because the stresses resulting from the swelling and shrinking of the two materials can be dissipated more easily; however, some research works support the idea that thin bond lines with certain epoxy adhesives can also give strong and durable bonds between FRP and wood (Raftery et al. 2009).

The factors determining the durability of structural adhesive joints can be grouped into three categories: environmental (moisture and temperature), materials and the stresses to which the bond is subjected (Custodio et al. 2009). An interesting review of the influence of these factors on the durability of bonded joints is included in this article.

The methods for repairing structural timber pieces can be classified in three general groups: traditional repairs (carpentry-jointed repairs), mechanical methods (bolts and steel plates) and resin-based methods. Some architects and engineers are concerned about the use of resin repair methods, and they usually prefer traditional or mechanical methods. The main reason for this is based on the unproven long-term performance of these systems. Nevertheless, the other arguments against these techniques (irreversibility, stiffening at joints, performance under conditions of high atmospheric moisture content, etc.) can be considered simple limitations or conditions for the use of these systems that do not invalidate the system itself. An interesting discussion on this subject and the high performance of epoxy resins under unfavourable moisture content conditions are presented in some works (Wheeler and Hutchinson 1998).

Shear testing is often used to determine the performance of wood adhesives. Methods defined in EN 301 and EN 302 have been developed for thermosetting structural adhesives, and they are not used to characterise epoxy resins because these often use thick joints without any pressure (Arriaga 1986). An interesting experiment was carried out to evaluate different testing procedures specifically for epoxy adhesives using thick joints (Lavisci et al. 2001).

The aim of this work is to study the quality of bonding between two materials (wood and composite material) using epoxy formulations, and to analyse the influence of timber species, type of epoxy formulation and the influence of the finish of the wooden contact surface. The method proposed in this work is a compressive shear test based on ASTM D 3931 which was developed for gap-filling adhesives, and it is similar to ASTM D 905.

MATERIAL AND METHODS

Three main materials are considered in this work: timber, composite material (GRFP) and epoxy formulations. Three timber species have been used: Radiata pine (*Pinus radiata* D. Don), Laricio pine (*Pinus nigra* Arn.) and Oak (*Quercus robur* L.). Laricio pine and Oak are very common in old timber structures in Spain, the first is a coniferous species used in general throughout the country, and the second is one of the main hardwoods used in the north of Spain. Finally, Radiata pine was selected because of its high shear strength and the existence of previous studies of its mechanical properties using small defect-free specimens (Vignote 1984).

Three epoxy formulations from the firm Sika S.A. were used as adhesives. The first is "Sikadur 42 Anclajes" which is a three-component epoxy formulation (resin, hardener and quartz sand filler in a weight ratio of 7:4:40, respectively) designed as a grouting system with a density of 1900 kg.m^{-3} (hereinafter EF-1, Epoxy Formulation 1). The second one, "Sikadur 31 Adhesive – Normal type" is a two part adhesive and repair mortar based on a combination of epoxy resins and special fillers with thyrotrophic properties and a density of approximately 1700 kg.m^{-3} (EF-2). The third one, "Sikadur 52 Inyección" is a low viscosity two part epoxy resin used for injection with a density of approximately 1100 kg.m^{-3} (EF-3).

Fibre reinforced polymers in two different formats were used: mat glass fibre reinforced plates of polyester resin and 13, 15 and 20 mm thick; and solid circular cross-section polyester resin reinforced rods with roving glass fibre 10, 16, 18 and 20 mm in diameter. The weight ratio of the glass fibre in these products varies from 50 to 70 %. These products were provided by three different manufacturers: Bremen SA (manufacturer A), Nioco SA (B), and Polymec SA (C).

Epoxy formulation properties

The bending strength and modulus of elasticity of the epoxy formulations were obtained by three point load tests in three 20x20x300 mm specimens according to the Spanish standard procedure of UNE 56537: 79. The compression strength was obtained in four 20x20x60 mm specimens following the procedure of the UNE 56535: 77 standard. Both standards are set for small defect-free timber specimens (Fig. 1), and in this way results are comparatively closer to timber properties without size affecting the results.

The main mechanism by which load is transmitted from timber to the reinforcement element in these kinds of repair techniques is shear stress. There is no standardized test to obtain this mechanical property for mortars; the shear test according to procedure of Spanish standard UNE 56543: 88 was therefore used. This is equivalent to the ASTM D 143 standard for wood. The epoxy formulation specimens were manufactured by pouring the mortar into moulds of the same shape as the wooden specimens (Fig. 1b). Four specimens were tested for each epoxy formulation (three specimens for EF-3) at 1, 7 and 21 days after curing, in order to obtain the velocity of strength increase.

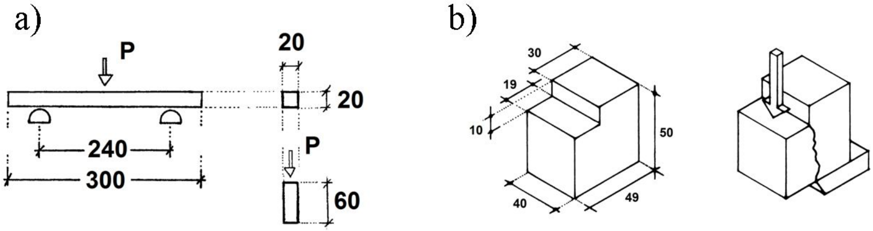

Fig. 1: Bending and compression test (a), shear test specimen (b) (mm).

Timber gluing

The bonding shear strength of glued lines was obtained according to ASTM D 905. This method consists of shear testing glued lines by means of a compression load. The dimensions of the specimen are shown in Fig. 2. The thickness of glued line was 1.5 to 2.5 mm in EF-1, 0.5 to 1 mm in EF-2 and 0.8 mm in EF-3. The results of the test are the shear strength (maximum load divided by the rupture area, 50x40 mm) and the Wood Failure Percentage (WFP), area of torn off wooden fibres.

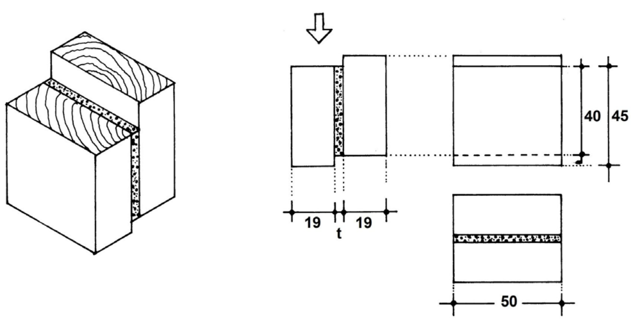

Fig. 2: Bonding shear test in glued lines (mm).

Two types of termination were used to evaluate the influence of timber contact surface roughness: a rough sawn (unplaned) and a planed surface. For this purpose, 16 specimens of each species and for each epoxy formulation were tested at 7 days for each surface termination (except for EF-3, with 8 specimens, and EF-1 and EF-2, with 7 specimens in Oak).

Glass fibre reinforced polymer properties

In order to discover the main mechanical properties of these products, their bending strength and modulus of elasticity were obtained according to the procedure of EN-ISO-178: 2003. The bending test consists of a concentrated central load in a simple supported beam (Fig. 3). 10, 16, 18 and 20 mm diameter bars were tested, with spans of 170, 220, 250 and 270 mm, respectively (four specimens for manufacturers A and B, and six specimens for manufacturer C). Mat plates 13, 15 and 20 mm thick and 20 mm wide were tested, in spans of 240, 240 and 270 mm, respectively, with the load parallel to the plane of the plate (eight specimens for each thickness).

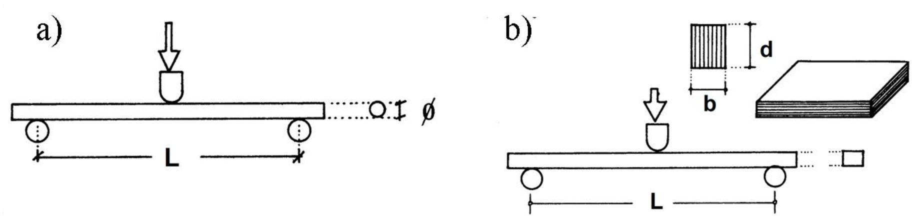

Fig. 3: Bending tests of reinforced polymers products: a) bars (a), b) plates (b)(mm).

Glued glass fibre reinforced polymers

The bonding shear strength of glued composite materials was tested in a different way for mat plates and bars. For 15 mm thick plates, shear tests by compression load similar to those for the bonded timber specimens were performed in four specimens for each epoxy formulation, but with smaller specimens (a rupture area of 40x31 mm) (Fig. 4).

For rods, the shear test by tension load was used to obtain the rupture shear stress in a 20 mm length of a 10 mm diameter bar (Fig. 5), (three specimens for each manufacturer). Both tests were made using two different surface treatments: firstly simple cleaning with a solvent (Ducol) and secondly lighting sanding (no. 100 sandpaper) and cleaning with solvent.

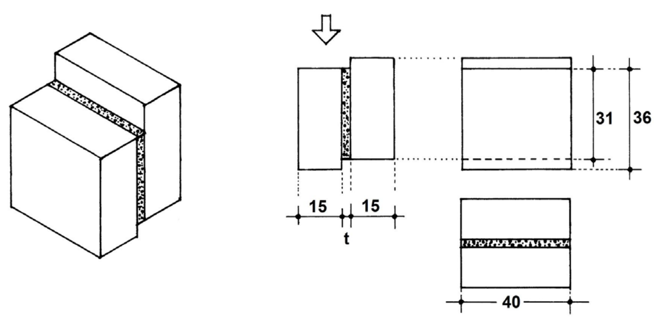

Fig. 4: Shear test specimen for bonding in plates (polyester resin reinforced with mat fibre glass) (mm).

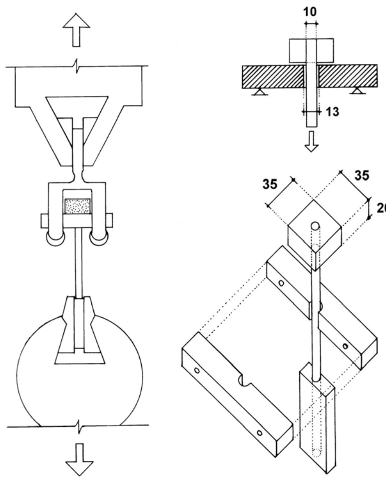

Fig. 5: Shear test for bonding in rods by tension load (mm).

RESULTS AND DISCUSSION

Tab. 1 shows the results of bending and compression tests of the three epoxy formulations. The bending strength is approximately from 28 to 38 N.mm^{-2}. The modulus of elasticity is approximately the half of coniferous timber species, except in EF-3 (only resin and hardener without fillers) with a very low MOE (541 N.mm^{-2}). The bending strength of epoxy formulation is not usually a critical parameter in this technique of timber structure repair, because the tension stresses of the bending moment is absorbed by the reinforcing materials. The MOE is lower in these formulations, but when epoxy is used as a material to partially substitute a timber piece it is used with a higher proportion of fillers, thereby raising the MOE to higher values than those for timber MOE. Compression strength is from 50 to 70 N.mm^{-2} which in general is higher than the compression strength of coniferous timber species.

Tab. 1: Mean values of bending and compression properties (N.mm^{-2}) and Coefficient of Variation (CoV) of epoxy formulations at 7 days.

Formulation	Bending		Compression
	MOR CoV (%)	**MOE CoV (%)**	**Rupture stress CoV (%)**
EF-1	28.7 6	4649 11	69.1 4
EF-2	31.7 8	3697 17	57.6 9
EF-3	38.4 8	541 9	49.3 29

The transfer of forces from timber to the reinforcing material takes place basically by means of shear stresses. Shear strength is approximately 19 N.mm^{-2} for the three formulations 21 days after setting (Tab. 2). This value is much higher than timber shear strength (coniferous timber species usually have an average rupture shear stress of from 9 to 12 N.mm^{-2}).

On the other hand, shear strength at 1 day is about 50 to 70 % of the strength at 21 days, and at 7 days this strength is very close to that at 21 days (84 to 94 %). The relationship between strength and time is shown in Fig. 6 for each formulation; the regression equations (with the logarithm expressing time) is included in the figure, while the determination coefficient is R^2 = 0.64 to 0.98.

Tab. 2: Age of the formulation and mean values of shear strength.

Formulation	Age (days)	Shear strength (N.mm^{-2}) - CoV (%)
EF-1	1	13.7 - 9
	7	15.9 - 8
	21	18.6 - 11
EF-2	1	10.9 - 26
	7	18.0 - 5
	21	19.5 - 14
EF-3	1	9.5 - 1
	7	16.3 - 4
	21	19.0 - 2

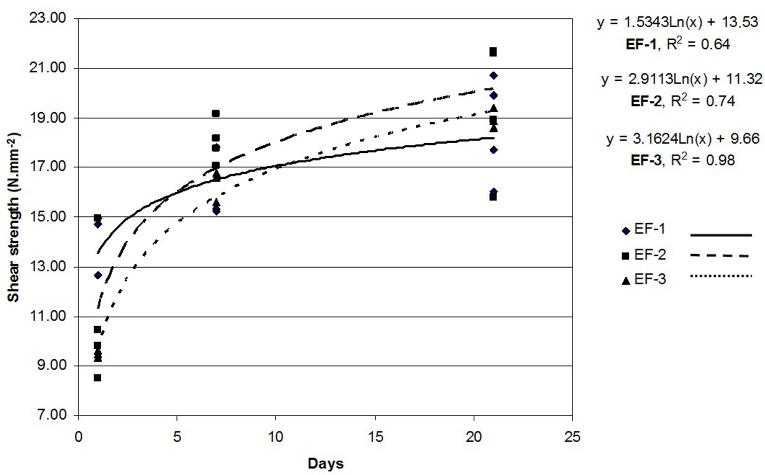

Fig. 6: Relationship between shear strength and age of the formulation.

In Tab. 3 bonding shear stress results are summarized for each formulation, each species and two different degrees of contact surface roughness (planed or unplaned timber) at 7 days from setting. It seems obvious that surface roughness influences bonding quality (shear strength and Wood Failure Percentage - WFP). The results show that the unplaned surfaces have higher shear strength and WFP, although this could not be confirmed in all of the cases studied because statistical analysis did not show significant differences. Fig. 7 shows a One-Way Anova means plot for cases with statistically significance differences.

Tab. 3: The effect of surface on bonding shear stress at 7 days age.

Formulation	Species	Surface roughness	Shear stress ($N.mm^{-2}$) - CoV (%)	WFP (%) CoV (%)
EF-1	Radiata p.	planed	9.6 – 33	32 – 63
		unplaned	9.5 – 16	37 – 31
	Laricio p.	planed	7.8 – 16	92 -15
		unplaned	8.3 – 18	88 – 24
	Oak	planed	11.3 - 24	56 – 44
		unplaned	15.1 – 7	79 – 20
EF-2	Radiata p.	planed	10.2 – 10	61 – 29
		unplaned	11.5 – 12	54 – 57
	Laricio p.	planed	9.4 – 10	98 – 3
		unplaned	8.8 – 16	100 – 0
	Oak	planed	13.1 – 12	40 – 57
		unplaned	13.8 – 12	87 – 17
EF-3	Radiata p.	planed	9.5 – 13	56 – 44
		unplaned	11.9 – 11	87 – 28
	Laricio p.	planed	8.1 – 8	75 – 38
		unplaned	8.9 – 16	99 – 4
WFP: Wood Failure Percentage				

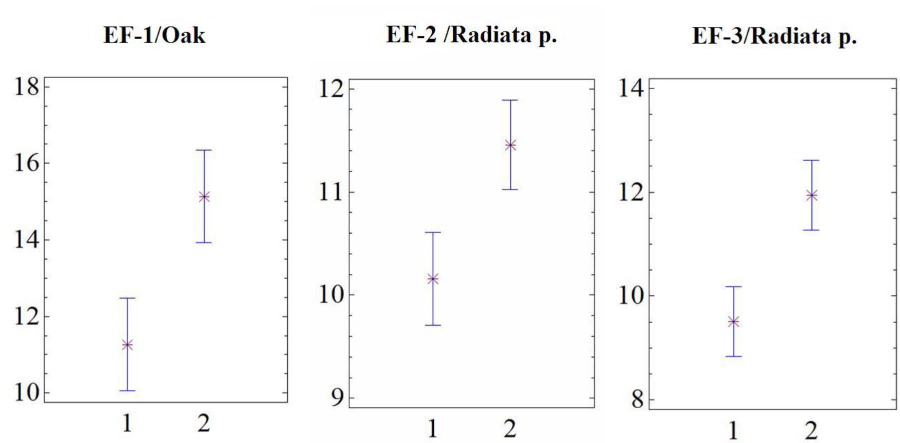

Fig. 7: One-Way Anova means plot of shear stress ($N.mm^{-2}$) for surface roughness (1: planed, 2: unplaned).

The average rupture shear stress of the Spanish species studied is 11 $N.mm^{-2}$ for Radiata pine (Vignote 1984), 8.5 $N.mm^{-2}$ for Laricio pine (Conde 2003) and 9.3 to 11.5 $N.mm^{-2}$ for Oak (Guindeo et al. 1997)

The average bonding shear strength for these species is 10.3 – 8.6 and 13.3 $N.mm^{-2}$ for radiata, laricio pines and oak, respectively. The results of bonding shear strength tests of unplaned surfaces in coniferous species are below the shear strength of timber only in the case of EF-1.

Tabs. 4 and 5 include the summary of bending properties of composite materials (bars and plates). The bars have a bending strength from 467 to 859 $N.mm^{-2}$ and they vary greatly depending on the manufacturer. The modulus of elasticity has a lower variation approximately from 28000 to 35000 $N.mm^{-2}$. The mechanical properties of mat plates are less strong; their bending strength is from 247 to 267 $N.mm^{-2}$ and their modulus of elasticity is approximately from 13000 to 16000 $N.mm^{-2}$.

Tab. 4: Bending properties of GFRP bars.

Manufacturer	**Diameter (mm)**	**MOR ($N.mm^{-2}$) - CoV (%)**	**MOE CoV (%)**
A	10	650 – 5	29975 – 3
	16	589 – 8	30730 – 2
B	10	624 – 8	30016 – 5
	20	467 – 8	33407 – 4
C	10	859 – 4	35231 – 2
	18	595 – 6	27925 – 3

Tab. 5: Bending properties of mat plates.

Thickness (mm)	MOR ($N.mm^{-2}$) - CoV (%)	MOE ($N.mm^{-2}$) - CoV (%)
13	247 – 14	13220 – 8
15	267 – 9	15283 – 7
20	252 – 6	16061 – 13

Tab. 6 shows the results of bonding shear stresses in plates for each epoxy formulation (at 7 days) and the effect of the surface treatment (c: cleaning with solvent, s+c: sanding and cleaning with solvent). It may be observed that previously sanded surface gives rise to no statistically significant differences in shear strength, although for the Glass Fibre Failure Percentage (GFFP) there are significant differences for EF-3 (Fig. 8). This behaviour may be explained because the low viscosity of EF-3 allows it to easily fill the irregularities of the sanded surface. On the other hand, the higher viscosity of EF-1 an EF-2 works better on the unsanded surface of the composite material (Fig. 8).

Tab. 6: Bonding shear strength in 15 mm thick plates and the effect of surface finishing.

Formulation	Surface treatment	Shear stress (N.mm^{-2}) - CoV (%)	GFFP (%) CoV (%)
EF-1	c	12.6 – 9	82 – 26
	s+c	11.2 – 21	98 – 5
EF-2	c	11.8 - 16	78 – 39
	s+c	11.2 - 29	52 – 108
EF-3	c	7.6 - 8	39 – 107
	s+c	9.2 - 23	100 - 0

c: cleaning with solvent
s+c: sanding and cleaning with solvent
n: number of specimens
GFFP: Glass Fibre Failure Percentage

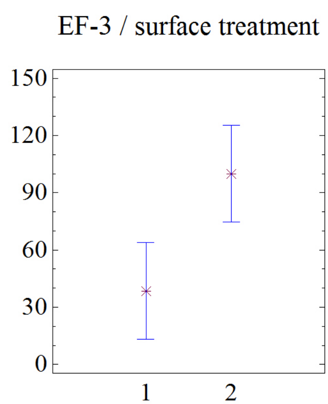

Fig. 8: One-Way Anova means plot of GFFP in % for surface roughness in EF-3 (1: cleaning, 2: sanding + cleaning).

The shear strength is from 7.6 to 12.6 N.mm^{-2}, which is a value of the same order or slightly higher than that of the ultimate shear stress in timber, so that therefore the critical parameter in a joint between timber and a composite material is the shear strength of the timber.

Tab. 7: Bonding shear strength in 10 mm diameter rods and the effect of surface finishing with EF-1.

Manufacturer	Surface treatment	Shear stress ($N.mm^{-2}$) - CoV (%)
A	c	17.9 – 5
	s+c	20.9 – 2
B	c	17.6 – 12
	s+c	17.8 – 5
C	c	16.9 – 5
	s+c	15.5 -10

c: cleaning with solvent
s+c: sanding and cleaning with solvent
n: number of specimens

Tab. 7 shows the results of bonding shear test in rods for the formulation EF-1 and the effect of surface treatment. The ultimate shear stress is approximately from 15 to 21 $N.mm^{-2}$, which is higher than the shear strength of timber. Previously sanding the surface does not give rise to any statistically significant differences.

CONCLUSIONS

The shear and compression strength of epoxy formulations are greater than those of timber, and therefore this material can be used for connexion with other materials and to substitute deteriorated timber under compression.

The increase in the shear strength of epoxy formulations over time after setting is remarkable. The strength at 1 and 7 days is at least 50 and 80 %, respectively, of the strength at 21 days, which is favourable for practical applications. The final strength (at 21 days) is independent of the type of epoxy formulation used.

The bonding shear strength between timber and a formulation is at least 9 $N.mm^{-2}$, which is a value close to the ultimate shear strength of timber. The influence of contact surface roughness (planed or unplaned) exists but have not been statistically confirmed. The results are slightly better for rough surfaces, and timber planed surfaces do not give rise to an advantage.

Regarding the bonding shear strength between composite material and the epoxy formulation, surface treatment of simple cleaning with solvent is enough, and it is not necessary to sand beforehand.

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